SMITHSONIAN INSTITUTION
ASTROPHYSICAL OBSERVATORY

METEORITE PHOTOGRAPHY AND RECOVERY NETWORK

Contract NsG 291-62

from the

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Semiannual Progress Report No. 8

1 January 1966 - 30 June 1966

Project Director: Fred L. Whipple

Scientist-in-Charge: Richard E. McCrosky

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TABLE OF CONTENTS

I. RESULTS FROM BRIGHT METEOR OBSERVATIONS

A. Orbital Elements

Orbital elements have been obtained for a significant number of the brighter Prairie Network meteors. In brightness, these objects form a nearly flat distribution (equal number of objects per magnitude group) in the -6 mag to -12 mag range. In Figure 1, the orbital elements a, e, and i, the perihelion distance q and the aphelion distance q' are compared with smoothed distributions (dashed lines) of the same parameters as obtained from 2500 faint Super-Schmidt meteors (McCrosky and Posen, 1961). The shower meteors were eliminated from both groups. Only one shower meteor, a Leonid, had been present in the Prairie Network sample. The elements are tabulated in Table 1, which also includes five objects that were reduced since the histograms in Figure 1 were drawn. The addition of these new objects does not significantly change the distributions.

It is immediately obvious that these distributions are, for the most part, dissimilar. Only the inclinations resemble one another, and even here there is an almost complete lack of retrograde orbits among the Prairie Network meteors. The new orbits are substantially smaller and less eccentric. The maximum of $1/a$ at 0. 4 corresponds closely to the mean semimajor axis of asteroids (although not necessarily of the Earth-crossing asteroids). The extreme paucity of very high-eccentricity orbits ($e > 0.95$) is most readily seen by inspection of the table. The aphelion distances of these meteors are mainly within Jupiter's orbit, with some indication of a maximum at the asteroid belt. The most peculiar and most unexpected result is the very high percentage of objects with perihelion between 0. 7 and 0. 8 a. u. (The peak near 1. 0 a. u.

is a selection effect due to the increased collision cross section for bodies with perihelion near the Earth.) The peak at 0.7 a.u. corresponds to Venus's orbit, but it seems inconceivable that this can be more than chance. We prefer to wait until further data substantiate this distribution before devising theories to explain it.

Cook, Jacchia, and McCrosky (1963) noted that the four high-density meteors known to be of asteroidal origin at that time formed two classes of objects with remarkably similar elements. This fact was written off as coincidence at the time, but it appears now that Group II may be a real class, comprised of the Czechoslovakian meteorite Pribram and Harvard Meteor 19816. The corresponding positions of these two groups of asteroidal objects are shown by the roman numerals on the graphs. Group II shows a strong preference for all the maxima. Inspection of the table will show that there are six individual meteors that can,. on the basis of a and q, be associated with this group. We wish to emphasize that this is not a shower phenomenon. These meteors occur at all times of the year, and the angular elements ω, Ω, and π do not bear a resemblance, except possibly for the meteors 39143 and 39154. The significance of a similarity in q (or a) and e alone (if real) is not clear at this time. It seems unlikely that it implies a common origin, although it may imply a similar origin, e.g., the method by which material is transferred from the asteroid belt to Earth-crossing orbits.

All of these highly speculative remarks may prove to be unnecessary and immaterial if additional data remove the spikes in the distributions that appear significant now.

B. Physical Characteristics

If one expects, as most students in the field do, that the percentage of the asteroidal objects increases as one looks at brighter objects, then the distribution showing a preponderance of small, low-inclination, and moderately eccentric orbits is not a surprise. In fact, the data and the arguments leading to the above conclusion are not overwhelmingly convincing, and the statement that the brightest meteors are asteroidal is more an article of faith than a proven fact. We have on hand now sufficient data to investigate the problem with rigor for the first time. To do this, we require, in addition to the orbit (which is at most a symptomatic parameter), a measure of some parameter that can distinguish cometary from asteroidal material. Differences in composition, structure, or density are all possible clues; the last of these is the most easily measured quantity and can be obtained, in principle, if the intensity and velocity of the meteor as a function of time are known. These are not available for all the cases listed in the table of orbital elements, where only the relatively simple parameters, the radiant and the preatmospheric velocity, are required. In some cases the duration of the meteor is too short to permit determination of the deceleration; in some cases the range of the object is so large that the trajectory solution is weakened; and in a few cases small unresolvable time errors are present that, although permitting a determination of the velocity, cause the first derivative of this quantity to be poorly determined. The luminosity as a function of time is sometimes not available, either because of poor sky conditions or because the meteor was so bright that its image exceeds the range where reasonable photometry can be accomplished. More often, we have not yet completed the laborious photometric analysis that we have found necessary to apply to these types of observations.

To summarize a tentative result immediately, we find that the physical characteristics of these bodies with presumably asteroidal-type orbits are not greatly different from the smaller and putative cometary objects observed with Super-Schmidts and reduced by Jacchia and Whipple (1961). That is, by employing the same theory and by utilizing many of the same modes of reduction, we find that these very bright bodies are of relatively low density suffering from relatively high mass-loss rates, a result inconsistent with the tough, high-density material expected from asteroidal meteorites. Three possibilities appear obvious: 1) the orbits are in error; 2) the theory or dynamical analysis yielding the low densities is in error; or 3) there are, in the solar system, a sizable number of large, fragile, low-density bodies (of either asteroidal or cometary origin) in small orbits. There is no reason to doubt the orbits, and to assume that 3) is true represents a rather radical change in thinking. Hence, we have initially concentrated on an investigation of the theory and the reduction techniques. It is appropriate at this time to discuss in detail meteor theory and its application.

C. Meteor Theory

The fundamental observations, position along the trajectory line as a function of time, and intensity as a function of time can be given immediate application through two fundamental equations. The first is the drag equation:

$$m \frac{dV}{dt} = - \Gamma A \rho V^2 \quad , \tag{1}$$

in which V is the velocity, ρ the atmospheric density, and m and A, respectively, the mass and frontal area of the body, all at time t; $\Gamma = C_D/2$ = the drag coefficient. For a spherical body of bulk density δ and radius r the equation can be rewritten as

$$r\delta = \frac{-0.75\ \Gamma \rho V^2}{\dot{V}} \quad , \qquad (2)$$

where the error in the determination of the unknown quantity on the left is governed almost entirely by the error in $\dot{V}$. The explicit assumptions, in addition to the assumed shape of the body, are that the drag coefficient and the density of the atmosphere as a function of height are known. Errors introduced by these last two postulates are small. Sufficiently large departures from sphericity are unlikely, and in any case a spherical shape is a good statistical hypothesis. An implicit assumption is that the center of light of the meteor is also the center of mass of the meteoroid, or, more specifically, that these two centers differ from one another by a distance that is constant with time. This is not exactly true, for example, in the case of a meteor with a luminous wake that increases in length with the function of time. The center of light will progressively lag the center of mass. Errors from this effect are thought, but not proven, to be small.

The second fundamental equation is one that purports to relate the luminous intensity of the meteor with the mass of the meteoroid. Given a valid form of this equation, we can determine the mass of the meteoroid independently and thus solve equation (2) for the density, or, more specifically, for the ballistic parameter m/A. A general form for the luminosity equation might be

$$I = f(m, V, \rho, A) \quad ,$$

but it was noted early in meteor astronomy that the majority of the light emitted by the meteor was emission-line radiation from meteoric gases. A reasonable simplification of the above equation is:

$$I = \frac{\tau}{2} \dot{m} V^2 \quad .$$

The constant τ is the luminosity factor and is a measure of the efficiency of the conversion of the meteoroid's kinetic energy to visible radiation. Öpik's computed values of τ have been approximated by Whipple as

$$\tau = \tau_0 V, \; (\tau_0 = \text{const.})$$

$$m(t) = \frac{2}{\tau_0} \int_{\infty}^{t} \frac{I}{V^3} \, dt \quad . \tag{3}$$

That this form of the equation is substantially correct for small bodies has been demonstrated by Verniani (1964). A numerical integration of the observed light curve (intensity vs time) yields a "photometric" mass for the meteor.

A third equation, the energy-transfer equation, is not fundamental to the problem of determining bulk densities of the meteoroid but does offer additional physical insight into the meteor process:

$$\dot{m} = - \frac{\Lambda}{2\zeta} A \rho V^3 \quad ; \tag{4}$$

ζ is the energy required to ablate a unit mass of meteoric material, and Λ is the fraction of the incident energy available for this process. Equations (1) and (4) can be combined, assuming a constant Λ, to give

$$m_1 = m_0 \, e^{\frac{\sigma}{2}\left(V_1^2 - V_0^2\right)}, \; \sigma = \frac{\Lambda}{2 \Gamma \zeta} \quad . \tag{5}$$

The differential form of the equation $\sigma = m/m V \dot{V}$ and the intensity equation yield

$$\sigma = \frac{I}{\left(\int \frac{I\,dt}{V^3}\right) V^4 \, \dot{V}} \quad . \tag{6}$$

If an exponential atmosphere is assumed, equations (5) and (1) can be combined to give a distance-dependent solution of the form

$$\left[E_i(u_a) - E_i(u_b)\right] e^{-u_b} = \frac{\beta(\rho_b - \rho_a)}{\nu_b \cos Z_R} \quad ,$$

where $u = (\sigma/6)\, V^2$; β = atmospheric scale height; $\nu = m/A$; and Z_R = zenith distance of radius, or angle of entry into atmosphere.

The general theory was found to fail for the Super-Schmidt meteors. The dynamical mass determined from the drag equation decreases with time at a far more rapid rate than does the photometric mass, a phenomenon that was attributed by Jacchia (1955) to progressive fragmentation of the body. The methods of measuring and acounting for this fragmentation have been developed by Jacchia (1955) and Verniani (1964). However, it was not, to our knowledge, realized that this very fragmentation phenomenon also implies a correction to the photometric mass. The original theory assumed, tacitly in fact, that all mass loss was by vaporization.

What effects come into play if part of the mass is lost by some other fragmentation process, either by shedding molten droplets or by splitting off solid particles? The effects, of varying importance, are as follows:

1) The fragment decelerates with respect to the parent body. Its evaporation products enter the air stream at a lower velocity than that assigned to the parent body, and, if equation (3) is correct, produce less luminosity per unit mass. The total mass of the ensemble, parent body plus fragments, must then be larger than the photometric mass, derived from a constant velocity. For low-velocity objects, the correction factor can approach 2 for meteoroids that lose all of their mass in small liquid or solid particles.

2) Some luminosity from fragments is produced when it has lagged well behind the body and is lost in the shutter break. This effect will generally be small.

3) As has always been known, the photometric mass does not include the unablated remains of the parent body. The terminal mass of the parent body can be estimated by equation (5) if we employ the observed values of σ for the particular meteor and assign some reasonable velocity to the meteor at which ablation ceases. (Unless the initial velocity is very low, the exact value of the terminal velocity is not critical.) However, the value of σ may be quite high for the parent body, since it is losing mass by a low-energy process of melting and fragmentation. This does not hold for the fragment, which is small enough, presumably, to lose mass only by vaporization. A considerably smaller value of σ may be applicable to the fragment, thus increasing the terminal mass of the individual particles. Again, then, we are underestimating the initial mass of the meteor when we use photometric techniques.

4) If we assume that either the parent body or the fragments continue to ablate until the energy input falls below some given level, i. e., ρV^3 = constant, the fragment is again at an advantage in surviving since it will reach this minimum energy-input point higher in the atmosphere and at a higher velocity. From equation (5), it is seen that the relative terminal mass of the particle will be larger than that of the parent body.

5) Energy available for evaporation of the particle is in competition with the blackbody radiation from the particle. This decreases the effective value of Λ, and then σ, and is more important for the smaller particles than it is for the parent body.

Sample calculations for meteoroids losing all their mass by fragmentation indicate that at the lowest velocities (10 km/sec) total corrections as great as five for all these effects are required to the photometric masses. At velocities of 25 km/sec and greater, the correction factor is entirely negligible. These corrections should be applied if the meteor theory is to be a consistent one. Unfortunately, they cannot be applied unless one knows the percentage of mass lost by fragmentation. This is a quantity not given to us by the observations. It is, however, of some help to know the order of the possible error.

One of the successful methods of determining the luminosity coefficient τ_0 has been the observation and analysis of meteors to which an approximate density can be assigned a priori, i. e., asteroidal objects. Two such meteors have been selected from the Harvard collection (Cook, Jacchia, and McCrosky 1963) on the basis of their anomalously low value of the deceleration and, less quantitatively, the absence of severe fragmentation phenomena. The luminous efficiency derived from these results has been used in the analysis of the Prairie Network meteors. They were derived for relatively faint objects photographed on blue-sensitive film. We apply the number to bright objects photographed on panchromatic film. (Observations of artificial meteors on panchromatic and on blue films by Smithsonian and NASA-Langley suggest that the difference in sensitivity of the emulsion does not greatly affect the results.) We have always been aware of the possibility that the luminous efficiency will probably change as one reaches bodies of very large size and thus very high intensity. We expect intuitively that for bodies of given velocity this change will be a smoothly varying function. We expected then to be able to correct the luminous efficiency by a bootstrap operation after observing a statistically significant number of asteroidal objects of varying brightness. In fact, though, our faintest objects, -6 mag, with "asteroidal" orbits and with relatively low ablation rates, have deduced densities of the order of 1.0 to 0.2. If these are in fact asteroidal objects of density 3.5, a correction of 10 to 250 is required in the luminous efficiency for these bright objects. The increase presumably arises from gas-cap radiation and from oxidation of the meteoric species for those bodies penetrating deep into the atmosphere. Our own experience with large bodies in the suborbital velocity range from 6 to 8 km/sec observed under the NASA-MIT Trailblazer program suggested that a correction of the order of 2, but not 10, might be appropriate.

Differences in structural strength or ablation energy may also serve to distinguish between asteroidal and cometary objects. We are now selecting a few meteors with small ratios of initial to final mass, as determined from the deceleration analysis, to investigate in detail. One object in particular, JD 39128 (orbit not yet computed), seems promising. The photometric analysis is particularly good. Preliminary trajectory analysis indicates an initial-to-final mass ratio of only about 3. The initial and final velocities are 13.1 and 8.0 km/sec. These values and equation (5) give the very low value of 2.5×10^{-12} $(sec/cm)^2$ for the average ablation coefficient σ. Furthermore, the light curve is remarkably free of any major flares that can be indicative of severe fragmentation. We hope this will prove to be a reasonable case on which to anchor a new mass-luminosity scale for meteors of exceptional brightness.

III. FIELD OPERATIONS

The automatic camera stations continue to operate at high efficiency, and the few instrumental problems were handled in the field. Some revisional work may be done on the shutters and the programmers.

The improved methods of film processing and inspection (described in Semiannual Progress Report No. 7) have been most successful in expediting the flow of meteor photographs from Lincoln to Cambridge. Figure 2 shows the number of double- and multiple-station meteors photographed each month from January through May 1966.

IV. PERSONNEL AND TRAVEL

The project continues under the direction of Dr. Fred L. Whipple. Dr. McCrosky, scientist-in-charge, has a staff of eight under his direct supervision. Five of the staff members operate the field headquarters in Lincoln, Nebraska, assisted by two part-time film readers.

Charles A. Tougas, field supervisor, will resign in the near future to accept the position of station manager at the new western observatory being established by the Smithsonian Astrophysical Observatory near Tucson, Arizona. A replacement will be recruited.

Dr. McCrosky traveled to Lincoln, Nebraska, at the end of January to test the effectiveness and practicality of a rubidium-vapor magnetometer in meteorite search. The instrument was loaned to the project by the manufacturer, Varian Associates, for a 2-week trial period. It was determined that the usefulness of the magnetometer was too limited to justify its purchase. However, in certain cases (plowed fields, snow cover) the instrument would be a valuable search aid, and it is expected that in these instances we will lease the magnetometer on a short-term basis.

V. REFERENCES

COOK, A. F., JACCHIA, L. G., AND McCROSKY, R. E.

1963. Luminous efficiency of iron and stone asteroidal meteors. Smithsonian Contr. Astrophys., vol. 7, pp. 209-220.

JACCHIA, L. G.

1955. The physical theory of meteors. VIII. Fragmentation as a cause of the faint-meteor anomaly. Astrophys. Journ., vol. 121, pp. 521-527.

JACCHIA, L. G., AND WHIPPLE, F. L.

1961. Precision orbits of 413 photographic meteors. Smithsonian Contr. Astrophys., vol. 4, pp. 97-129.

McCROSKY, R. E., AND POSEN, A.

1961. Orbital elements of photographic meteors. Smithsonian Contr. Astrophys., vol. 4, no. 2, 84 pp.

VERNIANI, F.

1964. On the luminous efficiency of meteors. Smithsonian Astrophys. Obs. Spec. Rep. No. 145, 62 pp. (Also published in Smithsonian Contr. Astrophys., vol. 8, pp. 141-172, 1965.)

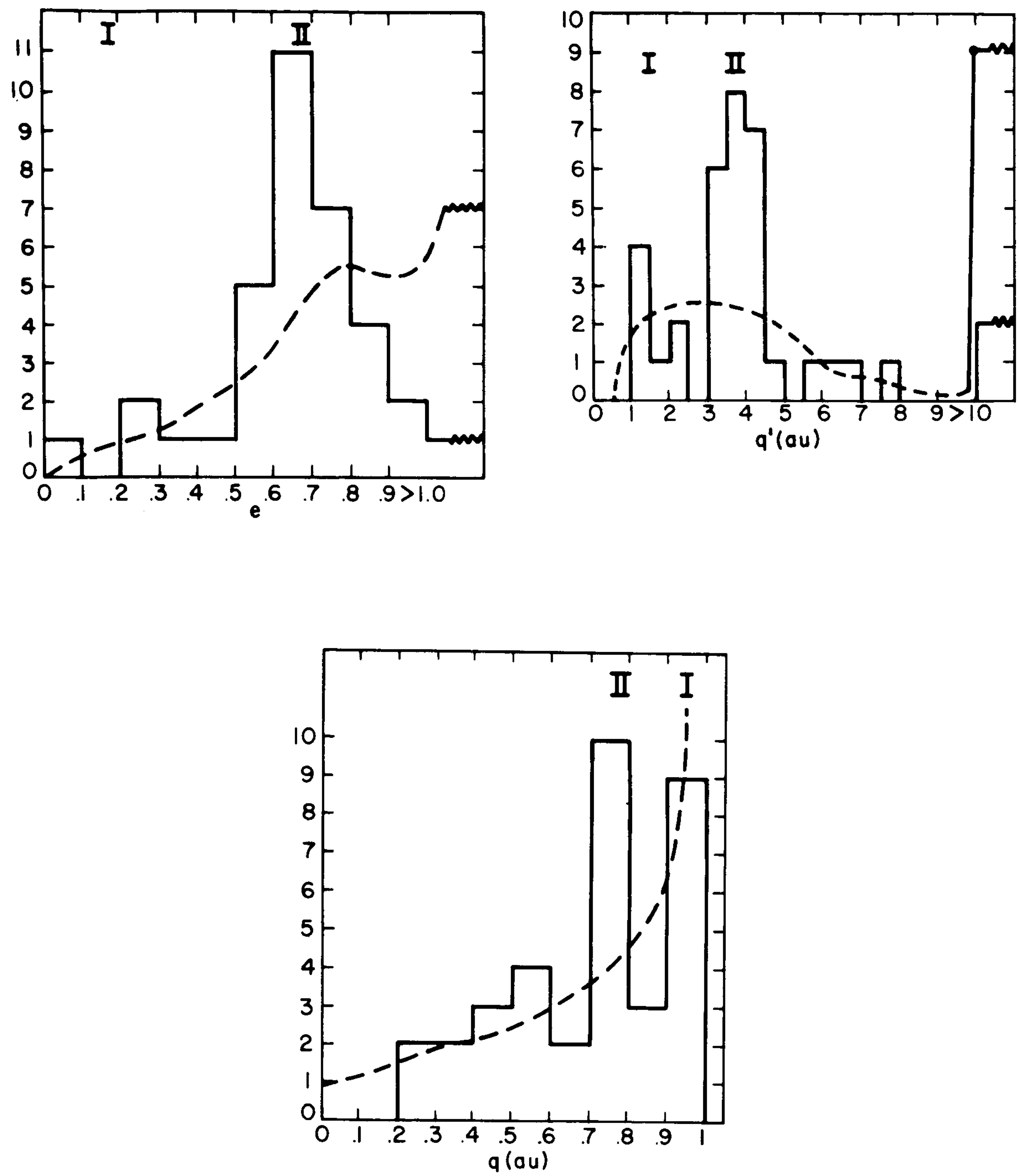

Figure 1. Comparison of distributions of orbital parameters of faint Super-Schmidt meteors and Prairie Network meteors.

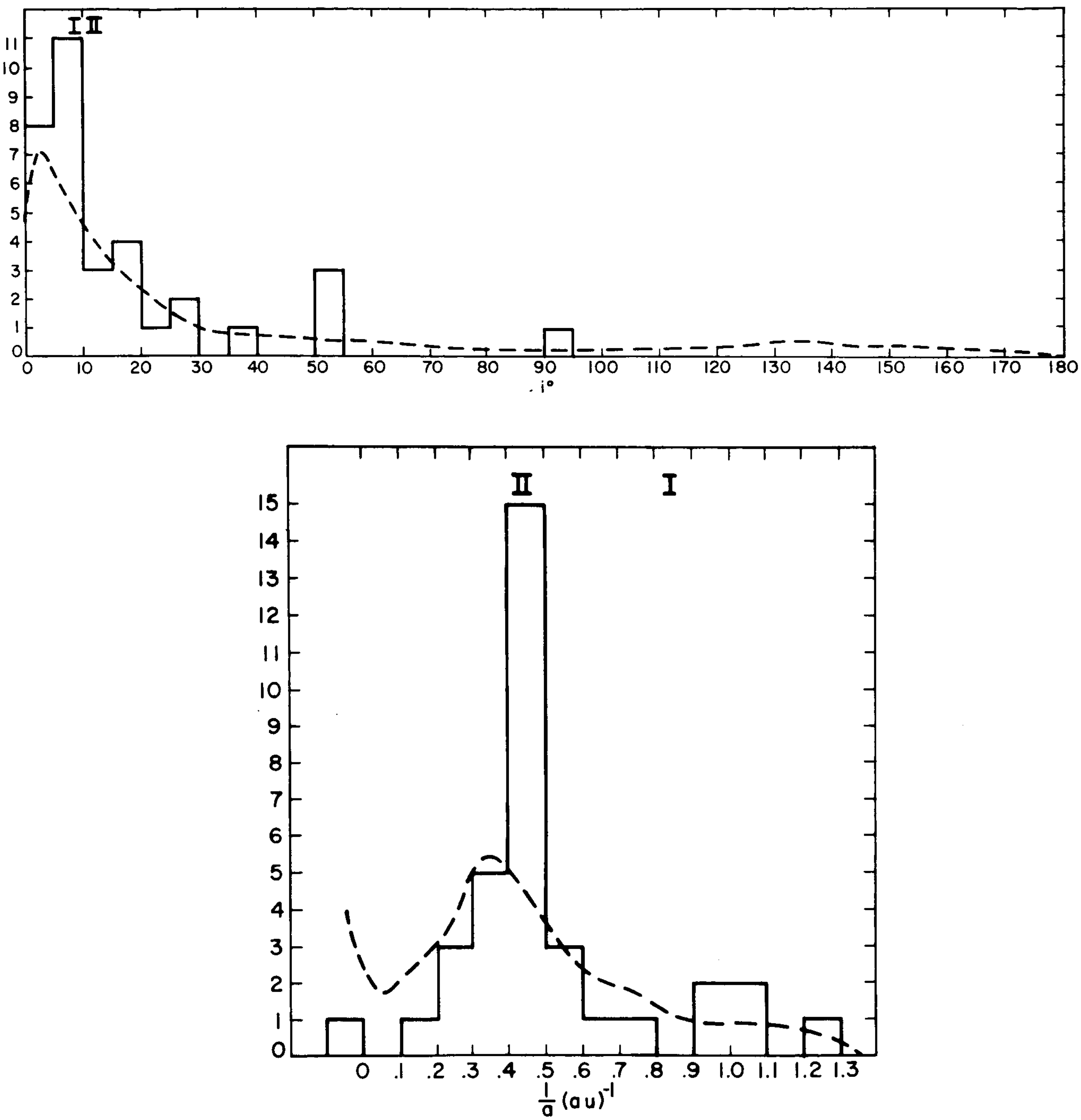

Figure 1. Continued

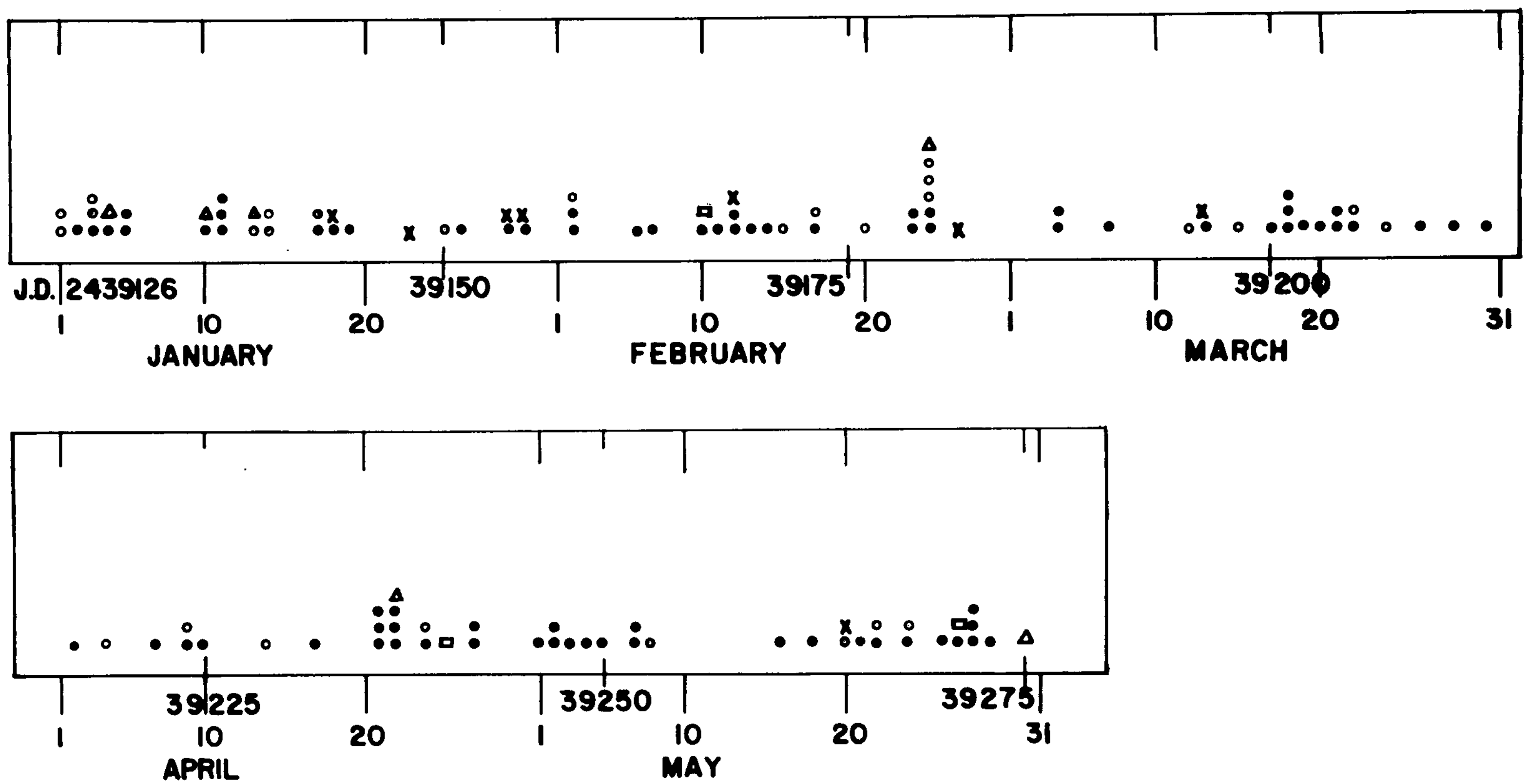

Figure 2. Double- and multiple-station meteors photographed by the Prairie Network from January to May, 1966. 2-station (x): 8; 5-station (□): 3 and 6-station (Δ): 6. Total: 125

Table 1. Orbital Parameters of Prairie Network Meteors.

Explanation of column headings used in Table 1.

λ	Elongation of the true radiant from the apex of earth's motion
a	Semimajor axis (a. u.)
e	Eccentricity
q	Perihelion distance (a. u.)
q'	Aphelion distance (a. u.)
p	Parameter of the orbit
ω	Argument of perihelion (degrees)
Ω	Longitude of ascending node (degrees)
i	Inclination of the orbit plane to the ecliptic (degrees)
V_{∞}	Preatmospheric velocity (km/sec)
V_G	Geocentric velocity (km/sec)

Table 1

λ	a	1/a	e	q	q'	p	ω	Ω	i	V_∞	V_G	JD
81	4.08	0.24	0.903	0.397	7.77	0.76	105	175	12	33.00	31.10	*8469
87	3.20	0.31	0.829	0.547	5.85	1.01	91	223	13	28.23	26.03	*8518
134	2.04	0.49	0.526	0.969	3.12	1.48	150	71	4	14.21	9.08	*8548
73	0.93	1.07	0.297	0.655	1.21	0.85	118	76	19	17.14	12.71	38737
101	1.62	0.62	0.521	0.777	2.47	1.18	67	79	2	17.36	13.29	38740
108	2.00	0.50	0.581	0.839	3.17	1.33	53	107	8	17.70	13.74	38768
80	2.08	0.48	0.647	0.736	3.43	1.21	250	347	39	29.40	27.30	38827
96	2.61	0.38	0.717	0.739	4.48	1.27	68	187	15	23.30	20.21	38847
89	2.22	0.45	0.739	0.580	3.86	1.01	269	10	2	25.10	22.45	38850
103	2.24	0.45	0.653	0.778	3.71	1.29	244	16	1	19.70	16.41	38856
74	0.97	1.03	0.223	0.756	1.19	0.93	291	39	26	18.80	14.89	38880
112	2.44	0.41	0.650	0.854	4.03	1.41	233	155	7	17.90	14.25	39000
99	2.04	0.49	0.648	0.717	3.35	1.18	74	5	4	20.52	16.90	39031
104	3.70	0.27	0.743	0.950	6.44	1.66	207	202	27	22.10	19.27	39048
76	1.96	0.51	0.846	0.301	3.62	0.56	121	22	6	31.80	29.46	39049
170	3.92	0.26	0.747	0.991	6.84	1.73	6	30	0	14.60	9.60	39057
80	2.66	0.38	0.627	0.994	4.33	1.62	180	213	50	31.50	29.59	39060
83	1.09	0.92	0.435	0.617	1.57	0.89	104	38	0	17.31	13.00	39065
136	1.01	0.99	0.025	0.988	1.04	1.01	12	51	0	10.80	0.29	39078
11	10	0.02	0.981	0.984	10	1.95	172	233	162	72.50	71.33	39080
76	2.30	0.43	0.600	0.921	3.68	1.47	215	233	52	32.60	30.66	39080
110	2.47	0.40	0.665	0.829	4.11	1.38	233	247	7	18.38	14.79	39093
82	2.66	0.38	0.845	0.411	4.91	0.76	106	67	5	29.70	27.89	39093
42			1.005	0.271			117	68	132	61.00	59.94	39094
122	1.96	0.51	0.535	0.912	3.01	1.40	218	267	5	15.03	10.30	39113
80	9.63	0.10	0.903	0.939	18.32	1.79	205	270	53	36.00	34.17	39116
94	2.22	0.45	0.660	0.756	3.68	1.25	245	274	22	23.00	20.19	39120
91	2.11	0.48	0.716	0.597	3.61	1.02	87	95	5	23.75	21.16	39121
100	2.95	0.34	0.756	0.721	5.19	1.27	248	276	9	22.60	19.49	*9122
84	2.32	0.43	0.796	0.474	4.17	0.85	100	104	8	28.20	25.75	39130
78	1.34	0.75	0.669	0.443	2.23	0.74	112	112	8	24.93	22.40	39138
100	2.25	0.44	0.671	0.741	3.75	1.24	247	298	6	20.45	17.42	39143
99	2.20	0.45	0.668	0.731	3.67	1.22	249	309	6	20.99	17.59	39154
98	2.62	0.38	0.713	0.751	4.49	1.29	65	151	14	22.20	19.36	39176
87	1.52	0.66	0.602	0.603	2.43	0.97	92	154	7	22.20	18.99	*9179
92	1.60	0.63	0.567	0.691	2.51	1.08	80	155	10	20.40	17.26	*9180
75	1.57	0.64	0.777	0.350	2.78	0.62	119	172	5	29.20	27.03	*9197
71	2.21	0.45	0.889	0.245	4.17	0.46	127	199	18	35.70	33.77	39224
111	2.05	0.49	0.532	0.961	3.14	1.47	210	34	17	17.15	13.26	39240

Note: *JD = Subject to Change